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EXPERIMENTAL DETERMINATION OF EXHAUST GAS THRUST

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SUMMARY

This investigation presents the results of tests made on a radial engine to determine the thrust that can be obtained from the exhaust gas when discharged from separate stacks and when discharged from the collector ring with various discharge nozzles. The engine was provided with a propeller to absorb the power and was mounted on a test stand equipped with scales for measuring the thrust and engine torque.

The results indicate that at full open throttle at sea level, for the engine tested, a gain in thrust horsepower of 18 percent using separate stacks, and 9.5 percent using a collector ring and discharge nozzle, can be expected at an air speed of 550 miles per hour.

INTRODUCTION

The exhaust gas contains an amount of energy equal to 50 percent of the energy of the fuel. It has been proposed (reference 1) that discharging the exhaust gas rearwardly provides a means of converting part of the energy in the exhaust gas into thrust horsepower. Two methods of obtaining exhaust jet reaction are:

1. Discharging the exhaust gas from separate stacks attached to each cylinder.
2. Discharging the exhaust gas from a nozzle attached to the exit of an exhaust collector ring.

In the first method the high potential energy in the cylinder is converted into kinetic energy in passing through the valve. The purpose of the exhaust stack is to direct the exhaust gas rearwardly with as little loss in kinetic energy as possible. Some further increase in

thrust may be obtained by attaching nozzles to the ends of the stacks.

In the second method, the greater part of the discharge velocity through the exhaust valve is lost when the gas enters the enlarged cross section of the collector ring with a resultant conversion of kinetic energy into thermal energy. In order to again obtain a high velocity of discharge, it is necessary to provide a nozzle at the exit of the collector ring with its attending increase in back pressure and loss in engine power. Obviously, from a power recovery consideration, the first method is superior to the second. Method 1, however, has the disadvantages of greater glare, noise, and danger from the exhaust gases; and in many installations method 2 would be preferable because of these practical considerations.

Present information on the thrust of the exhaust gas jets has been obtained mainly by calculation. The calculated thrust for separate exhaust stacks is given in reference 1.

Some experimental information on the thrust provided by the exhaust gas has been reported. Flight tests on an airplane equipped with a Rolls-Royce engine (reference 2) and on a Curtiss XP-40 equipped with an Allison engine indicate a gain in speed of 6 miles per hour at an air speed of 325 miles per hour. Both engines are in-line liquid-cooled engines. In the case of the Rolls-Royce engine, the exhaust pipes were connected in pairs, each pair having a common discharge passage. The chambers in each side of the engine provided at the junction of the pipes in each pair were connected by a passage. In the case of the Allison engine, each set of three adjacent cylinders was connected to a separate manifold provided with a rearwardly discharging port.

The present report presents the results of tests made on a radial engine mounted on a thrust stand to determine the thrust that can be obtained from the exhaust gas when discharged from separate stacks and when discharged from the collector ring with various discharge nozzles.

APPARATUS AND METHOD

A Pratt & Whitney 1340-H engine was used for this investigation. This engine has a compression ratio of 6, and

is rated at 550 brake horsepower at 2,100 revolutions per minute. This engine was operated with fuel injection into each cylinder. In the tests with the separate stacks, valve overlap was used; while in the tests with the collector ring, the normal timing was used. A 9-foot adjustable propeller, with a pitch setting to give the rated engine speed at full open throttle, absorbed the power. The engine was mounted on an outdoor test stand which was provided with scales for measuring engine torque and the thrust (fig. 1).

The separate exhaust stacks (fig. 2) were 2-1/2 inch O.D. steel tubing about 15 inches long. These tubes did not extend straight back but were bent radially outward at an angle of 15° with the axis of the crankshaft. Short elbows which deflected the exhaust gas normal to the crankshaft were fastened to the separate stacks to approximate a condition of no exhaust gas thrust. For the condition of exhaust gas thrust, small blocks with a frontal area equal to that of the short elbows were fastened to the separate stacks to compensate for the increased drag of the elbows (fig. 2).

The exhaust collector ring for this engine consisted of two semicircular manifolds with a common outlet. The area of the outlet was approximately 24 square inches. The opening pointed radially outward and 30° toward the rear. The manifold was mounted on the engine with the outlet at the same height as the propeller hub. The elbow, shown in figure 3a, when attached to the ring outlet, discharged the exhaust gas normal to the crankshaft which represented the no-thrust condition. The direction of the discharge for this elbow passed through the pivot for the dynamometer scale in order that the force provided by this discharge would not affect the dynamometer scale reading. The thrust elbow, shown in figure 3b, when attached to the manifold discharged the exhaust gas parallel to the propeller axis. The nozzles shown in figure 3c when connected to the thrust elbow increase the exhaust gas velocity at the expense of increased back pressure. The discharge nozzles and elbows had the following exit areas:

No-thrust elbow - - - - -	24.0 sq. in.
Thrust elbow - - - - -	24.0
Nozzle 1 - - - - -	11.4

Nozzle 2	- - - - -	7.7
Nozzle 3	- - - - -	5.4
Nozzle 4	- - - - -	4.2

Figure 4 shows the engine equipped with the exhaust collector ring, the thrust elbow, and a nozzle.

A tachometer for measuring the engine speed and manometers for measuring the inlet manifold pressure and discharge pressure were used. Aviation gasoline having a knock rating of 100 octane was used in the tests.

The method of obtaining the exhaust gas thrust consisted, in general, of making a run with the thrust device and with the no-thrust device for a range of engine powers in which the thrust scale, dynamometer scale, revolutions per minute, inlet manifold pressure, and exhaust pressure were read. In the absence of an air-fuel ratio meter, the air-fuel ratio was held approximately constant by leaning the mixture to the point at which further leaning resulted in a loss of power. (A plot was made of thrust against engine power for the thrust and no-thrust devices, and the difference in thrust for the same engine power was taken as the thrust provided by the exhaust gas. Tests were made only on days in which the wind velocity was very low.)

As the exhaust gas thrust is obtained by taking the difference between two nearly equal quantities, large errors might be expected. For this reason, several determinations were made with each thrust device.

A propeller efficiency, η , of 80 percent was assumed in the computations.

RESULTS AND DISCUSSION

Separate Stacks

Figure 5 shows the results of one of three determinations of exhaust gas thrust using separate stacks. The upper curve is the total thrust obtained with the exhaust jet issuing toward the rear. The lower curve is the thrust obtained with the exhaust jet deflected normal to

the crankshaft. The difference represents the exhaust gas thrust and is a small percentage of the total thrust. These curves show the necessity of obtaining data with very small dispersion. Some difficulty in obtaining smooth curves was experienced due to a tendency of the engine to "hunt."

The gas thrust obtained in three determinations is plotted in figure 6 against engine brake horsepower. Analysis shows that for a given rate of air and fuel consumption the exhaust gas thrust is a function of the gas temperature at the time the discharge valve opens and of the ratio of the corresponding cylinder pressure to atmospheric pressure. If it is assumed that the ratio of the cylinder pressure at the time of exhaust to the manifold pressure is a constant for a given engine and valve timing, then the exhaust gas thrust is a function of the ratio of the manifold pressure to atmospheric pressure. The exhaust gas thrust horsepower as a percentage of the propeller thrust horsepower is plotted in figure 7 against airplane velocity for two values of the ratio of manifold pressure to atmospheric pressure, P_m/P_o . The exhaust gas thrust horsepower was calculated from the gas thrust in figure 6 by means of the relation,

$$\text{thrust horsepower} = \frac{TV}{375} \quad (1)$$

where T is the exhaust gas thrust in pounds and V is the airplane velocity, miles per hour. This figure shows that the exhaust gas thrust horsepower at full throttle and 550 miles per hour airplane velocity is 18 percent of the propeller thrust horsepower.

These data were obtained with the engine fitted with cams having an overlap period of 130° . However, the overlap should have practically no effect on the thrust for a given engine power as any discharge of gas through the exhaust valve during the charging process would occur with a relatively low velocity.

Collector Ring

The test with the exhaust gas collector ring and nozzles was made with the engine fitted with the standard cams rather than the valve overlap cams because of the larger reduction in engine power with increase in back pressure

which was experienced with the valve overlap cams. The later closing of the exhaust valves with valve overlap permits flow of exhaust gases from the manifold back into the cylinders at inlet manifold pressures below the exhaust back pressure and increases the amount of residual gases.

Figure 8 shows the results of two determinations of the thrust obtained by discharging the exhaust gas rearwardly from the exhaust manifold using the thrust elbow (fig. 3b). These results are about two-fifths of the thrust gained by using separate exhaust stacks. This thrust is obtained with no decrease in discharge area and a negligible increase in back pressure introduced by the bend of the elbow.

Figure 9 shows the variation of exhaust gas thrust, maximum brake horsepower, and engine speed with exhaust back pressure obtained by using various discharge nozzles with the engine operating at full open throttle. Part of the reduction in engine power is the result of the decreased engine speed and could obviously be restored by changing the propeller pitch. The engine power was corrected to a constant engine speed (2,160 r.p.m.) and manifold pressure and the loss in power caused by back pressure was obtained by subtracting these corrected engine powers from the engine power with atmospheric back pressure. The loss in engine power is given in figure 10 as a percentage of the indicated horsepower of the engine, I , and is plotted against the ratio of the increase in back pressure to manifold pressure, $\Delta P_b/P_m$.

Part of this power loss is the result of the additional work of the piston in discharging the exhaust gas against the higher back pressure, E_p , and the remainder, E_r , is caused by the reduction in engine charge resulting from the increased weight of residual gas.

The following equations can be used for calculating E_p and E_r .

$$\frac{E_p}{I} = \frac{\Delta P_b}{P_m \Phi_i} \quad (2)$$

where

$$\Phi_i = \frac{550 I}{P_m V_D N}$$

$$\frac{E_r}{I} = \frac{\left(\frac{P_{e1}}{P_o}\right)^{1/\gamma_e} - 1}{\frac{r}{0.808} \left(\frac{P_m}{P_o}\right)^{1/\gamma_e} - 1} \quad (3)$$

where

r is the compression ratio.

P_{e1} , exhaust back pressure.

P_m , inlet manifold pressure.

V_D , engine displacement volume.

I , indicated horsepower.

N , number of cycles per second.

$$\Delta P_b = P_{e1} - P_o$$

P_o , atmospheric pressure.

γ_e , the ratio of specific heats of exhaust gases.

The calculated values of $(E_p + E_r)/I$ are shown, in figure 10, plotted against $\Delta P_b/P_m$ for various values of P_m/P_o . The experimental points are scattered but appear to indicate fair agreement with the calculated values.

The gas thrust shown in figure 9 was divided by the indicated horsepower and is shown in figure 11 plotted against the ratio of the increase in back pressure to atmospheric pressure $\Delta P_b/P_o$.

The theoretical thrust was calculated from the following equation and is also shown in figure 11.

$$\frac{T}{I} = \frac{W_e}{I} \sqrt{2Jg \ c_p \ T_{e1} \left[1 - \left(\frac{P_o}{P_{e1}}\right)^{\frac{\gamma_e-1}{\gamma_e}} \right] + V_{e1}^2} \quad (4)$$

nozzle formula

where

- T is the exhaust gas thrust.
- I , indicated horsepower.
- W_e , mass flow of exhaust gas.
- J , mechanical equivalent of heat.
- g , acceleration of gravity.
- c_{p_e} , specific heat of exhaust gases at constant pressure.
- T_{e_1} , temperature of exhaust gases.
- V_{e_1} , velocity of exhaust gases before the nozzle.

In calculating the value of T/I from the above equation, the assumption was made that the fuel-air ratio was 0.08, which corresponds to the optimum power condition; and the value of W_e was obtained from a calibration curve of the engine for this fuel-air ratio. The value of T_{e_1} was assumed to be 1,960° F. abs. The agreement between the experimental and theoretical curves is good in view of the assumptions made in calculating the latter curve.

For a constant fuel-air ratio it is reasonable to expect W_e/I and T_{e_1} to remain constant with change in inlet manifold pressure. From equation (4) it is evident that T/I should then be the same for the same value of P_{e_1}/P_0 regardless of altitude provided V_{e_1} and fuel-air ratio are held constant. Referring to equations (2) and (3) it is seen that when plotted as shown in figure 10 the loss in power with increase in back pressure is also independent of altitude.

Figure 12 shows the net thrust horsepower as a percent of the original indicated horsepower plotted against the ratio of the increase in exhaust back pressure to atmospheric pressure for two values of the ratio of the manifold pressure to the atmospheric pressure.

The quantity BHP_0 is the original brake horsepower with the normal collector ring discharge condition. The line marked "zero exhaust gas thrust" indicates the value of

$\eta \text{ BHP}_0/I_0$. The curves marked "experimental" and "theoretical" were obtained from similarly marked curves in figures 10 and 11. It is seen in figure 12 that at low airplane velocities a large part of the exhaust gas thrust is obtained by discharging the exhaust gas rearwardly with no increase in exhaust back pressure.

At each airplane velocity there is an optimum exhaust back pressure (fig. 12) at which the net thrust horsepower is a maximum. The difference between the maximum net thrust horsepower and the original thrust horsepower (no exhaust thrust) as a percentage of the original thrust horsepower is shown in figure 13 plotted against the airplane velocity for two values of P_m/P_0 . The optimum values of $\Delta P_b/P_0$ are also shown. As previously pointed out, these curves are independent of altitude provided that the fuel-air ratio and the velocity of exhaust gas in collector ring ahead of the nozzle are equal to the values which were obtained in the tests.

Figure 13 shows the following percentage increase in net thrust horsepower at an air speed of 550 miles per hour.

P_m/P_0	1	2
Experimental	9 percent	11.5 percent
Theoretical	7 percent	12 percent

Comparison of these values with the values obtained from figure 7 for the same air speed shows the marked superiority of separate exhaust stacks.

Some difference exists between the optimum value of $\Delta P_b/P_0$ obtained from the experimental and theoretical curves. This is not very serious as the value of the net thrust horsepower is not very sensitive to change in back pressure in the vicinity of optimum back pressure.

It may readily be shown that, for a given fuel-air ratio, ratio of the weight of exhaust gas per unit time to indicated horsepower, and nozzle discharge coefficient, the increase in exhaust back pressure as a ratio of atmospheric pressure $\Delta P_b/P_0$ is a function of the ratio of the discharge nozzle area to the manifold exit area ahead

of the nozzle A_2/A_1 and the quantity $I/A_1 P_0$ where I is the indicated horsepower, A_1 is the manifold area ahead of the nozzle, and P_0 is atmospheric pressure. For a given fuel-air ratio, the ratio of the weight of exhaust gas per unit of time to the indicated horsepower depends only on the indicated thermal efficiency, and should not vary appreciably between modern engines. The fuel-air ratio for the present tests is estimated at 0.08.

Figure 14 shows the values of $\Delta P_b/P_0$ plotted against $I/A_1 P_0$ for various values of A_2/A_1 obtained in the present tests. These curves provide a means for estimating the nozzle area to obtain a given increase in exhaust back pressure.

The present tests are in the nature of a preliminary study to show the magnitude of the jet propulsive force that might be expected. The method of measurement is not sufficiently accurate to detect small changes in thrust. A further study is required using more accurate measuring means to show the effect of exhaust-pipe length and diameter, bends, shape and size of exhaust nozzles, the effect of joining the stacks of various numbers of cylinders, and the effect of exhaust-valve opening time on exhaust-gas thrust.

CONCLUSIONS

1. Separate exhaust stacks provided considerably higher power recovery than an exhaust collector ring equipped with a discharge nozzle. At $P_m/P_0 = 1.16$ (full open throttle at sea level for the present engine) a gain in thrust horsepower of 18 percent using separate stacks and 9.5 percent using a collector ring and nozzle can be expected at an air speed of 550 miles per hour.

2. A large part of the exhaust thrust when using a collector ring is obtained by discharging the exhaust gas rearwardly with no increase in back pressure.

3. The amount of back pressure required for maximum net thrust horsepower when using a collector ring and nozzle increases as the airplane velocity increases.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 23, 1939.

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2. Hives, E. W., and Smith, F. L.: High Output Aircraft Engines. Abstract, Automotive Industries, July 1, 1939, pp. 22-24.

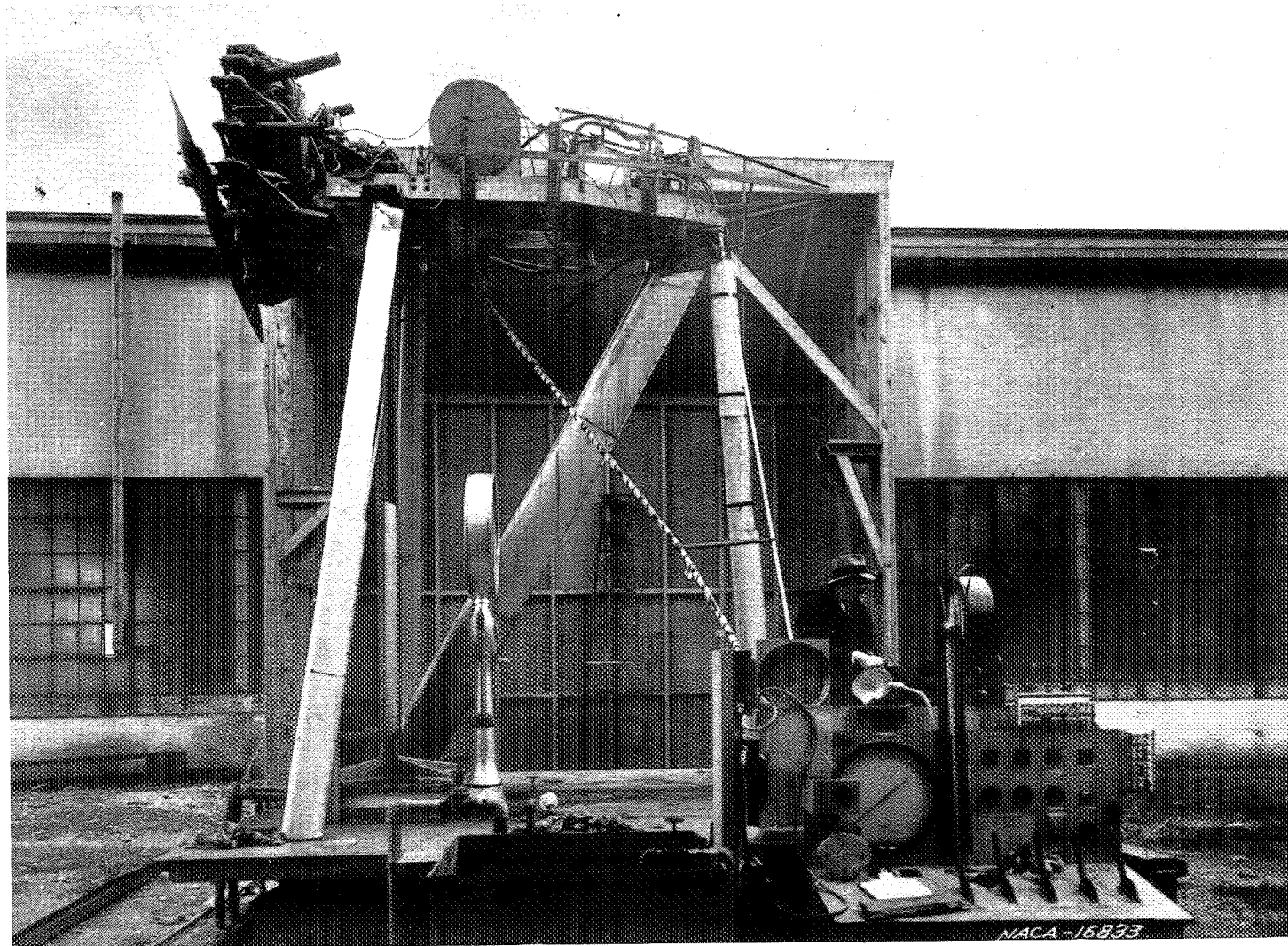


Figure 1.- Engine with separate exhaust stacks mounted on test stand.

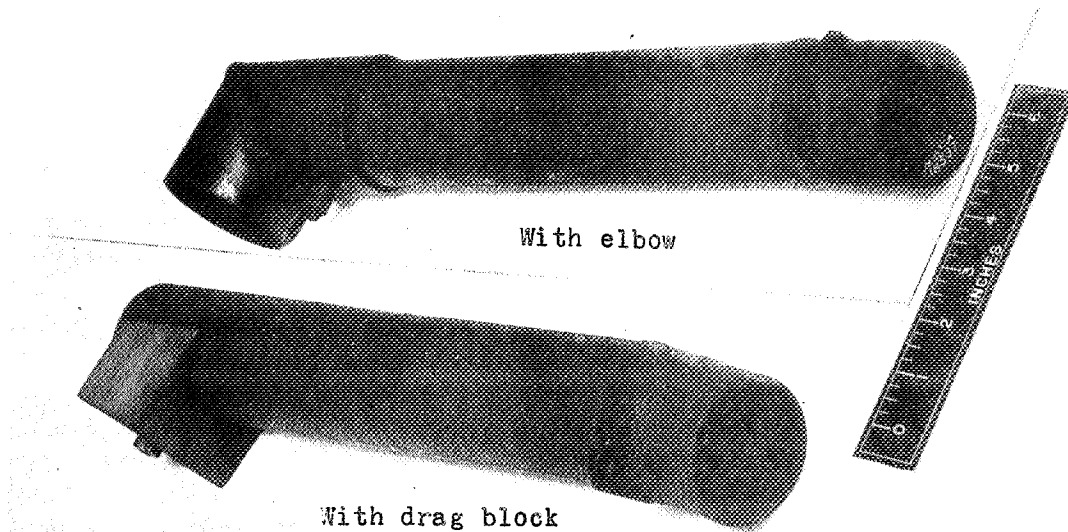


Figure 2.- An exhaust stack for gas thrust and no thrust conditions.

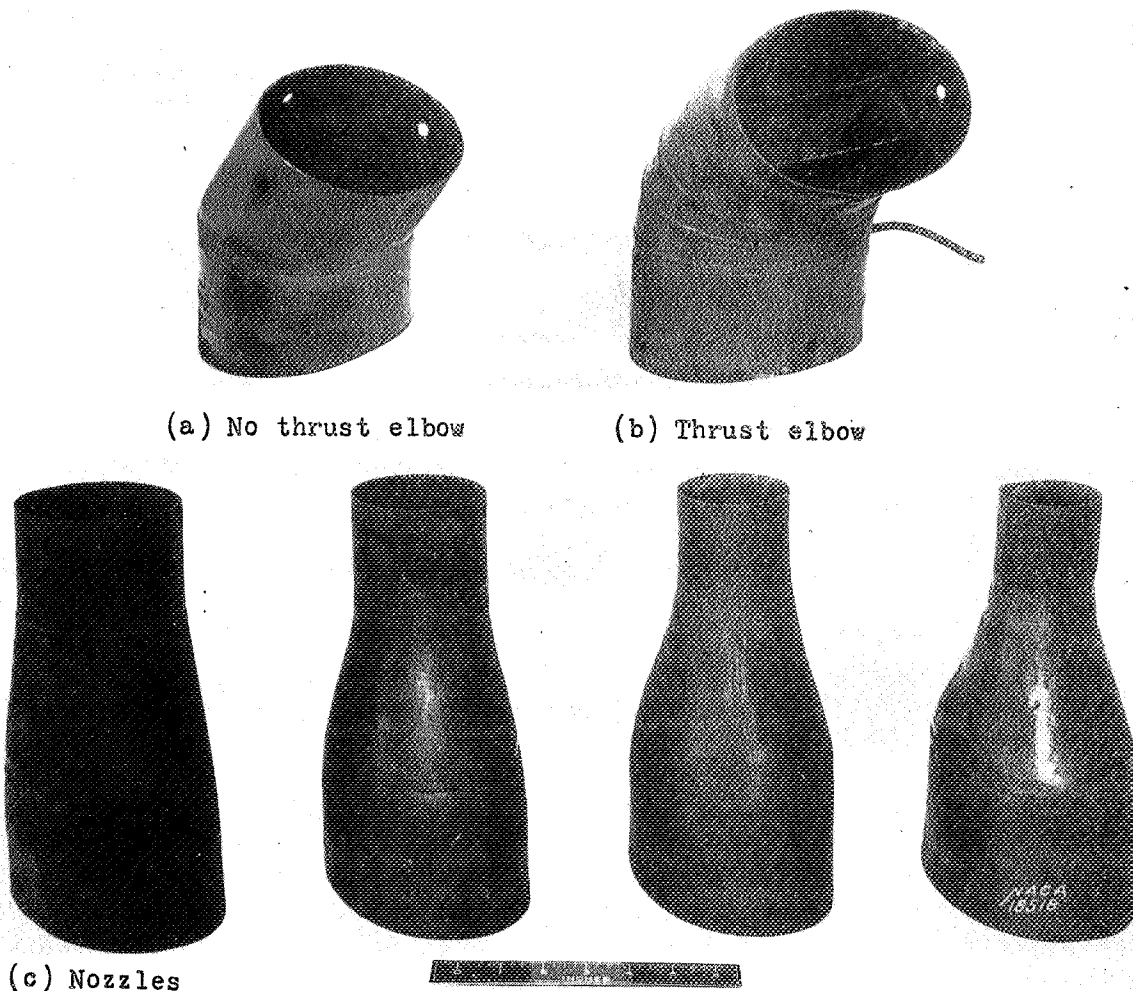


Figure 3.- Elbows and nozzles used with the exhaust collector ring.

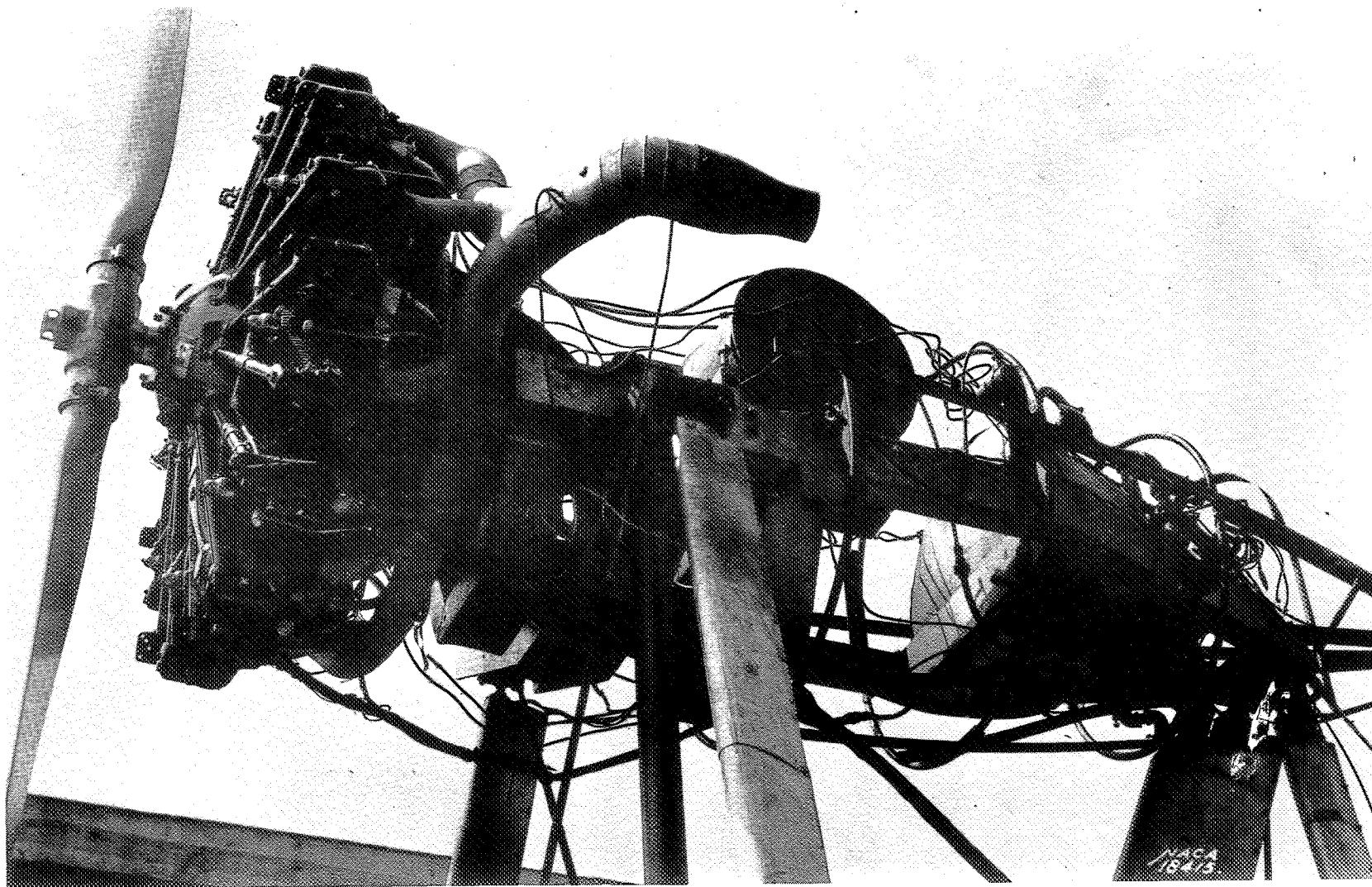
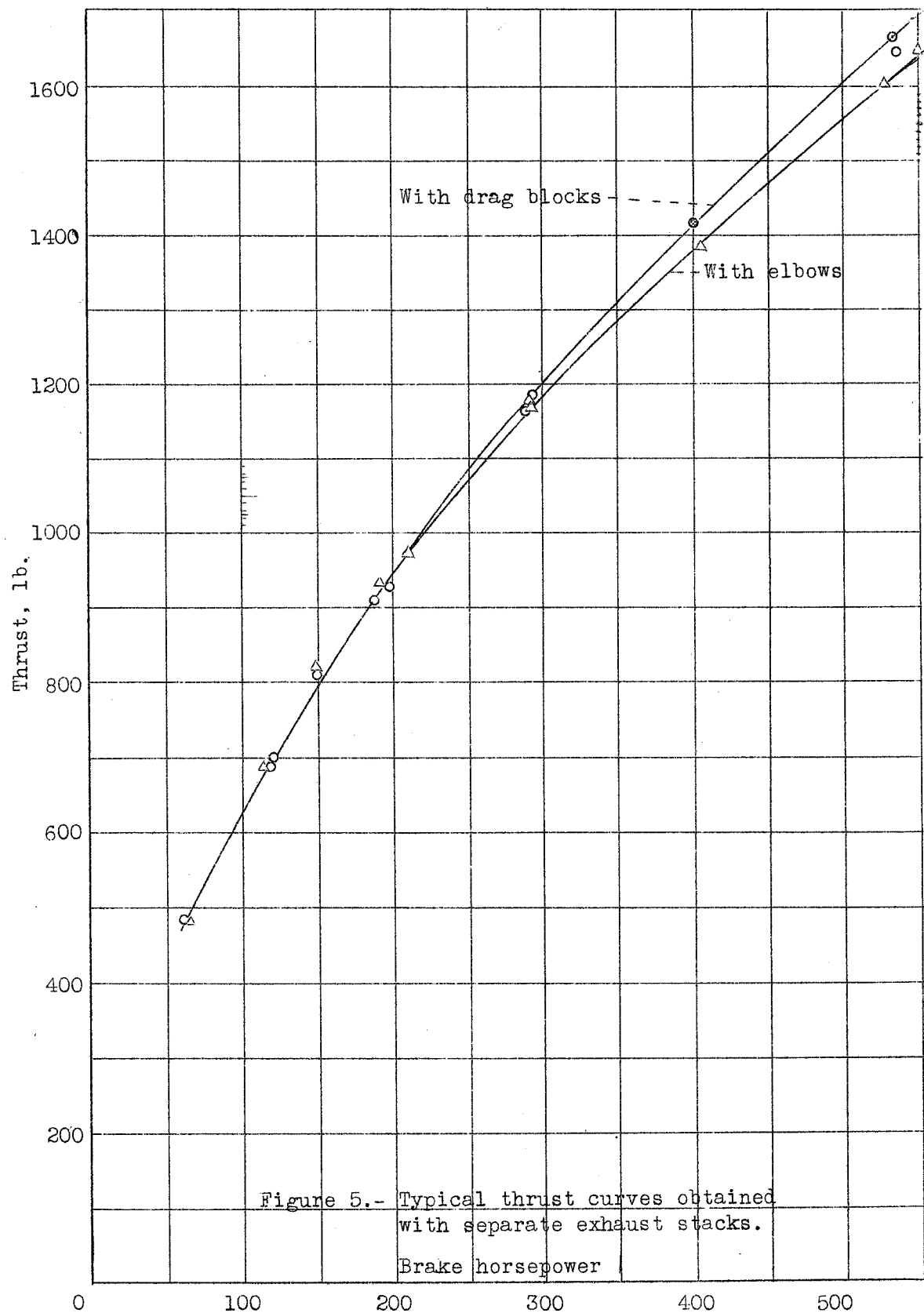


Figure 4.- Engine equipped with collector ring and nozzle.



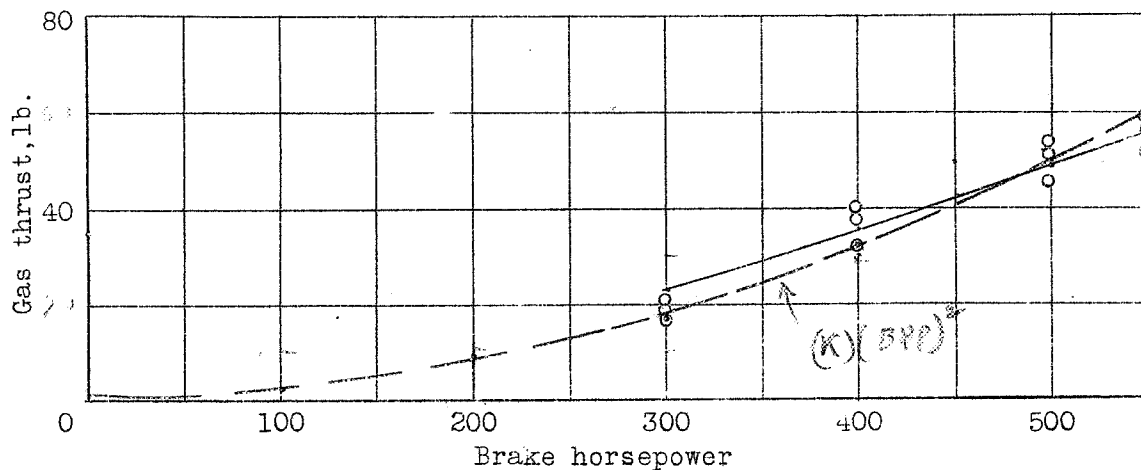


Figure 6.- Effect of engine power on exhaust gas thrust.
Separate stacks.

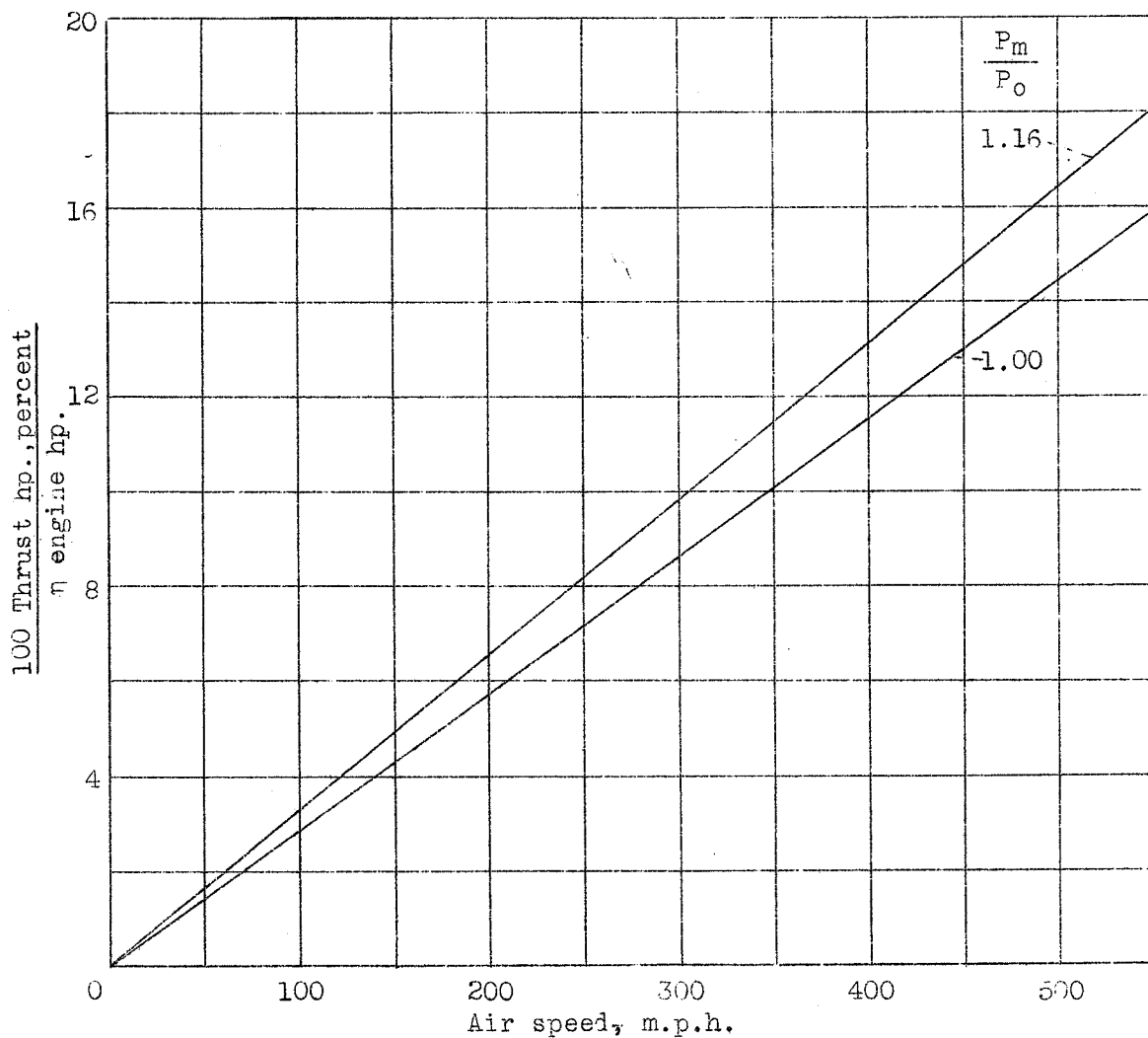


Figure 7.- Exhaust jet thrust horsepower at various power outputs and air speeds. η , propeller efficiency= 80 percent.

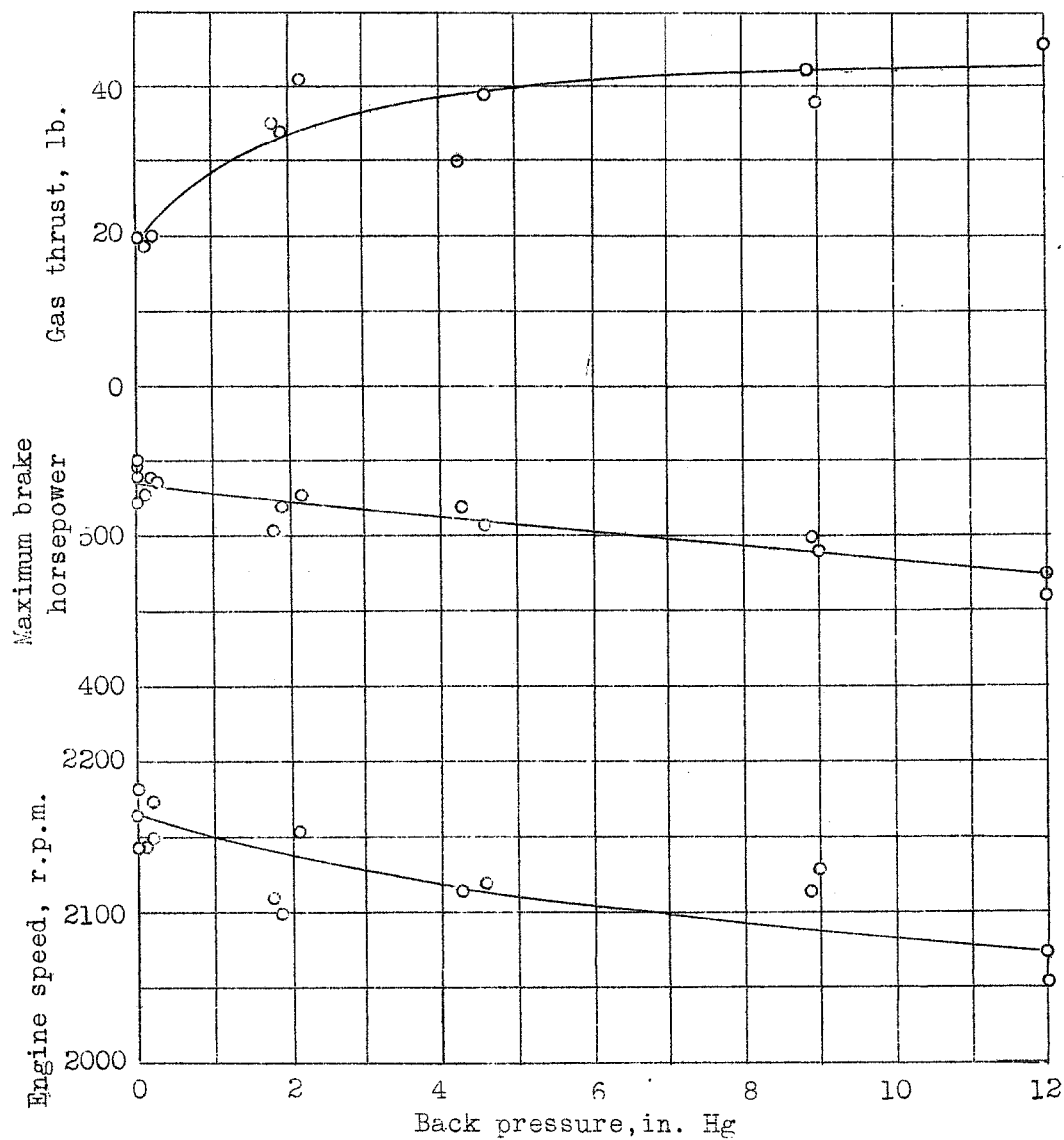


Figure 9.- Effect of back pressure on exhaust gas thrust, engine power, and engine speed.

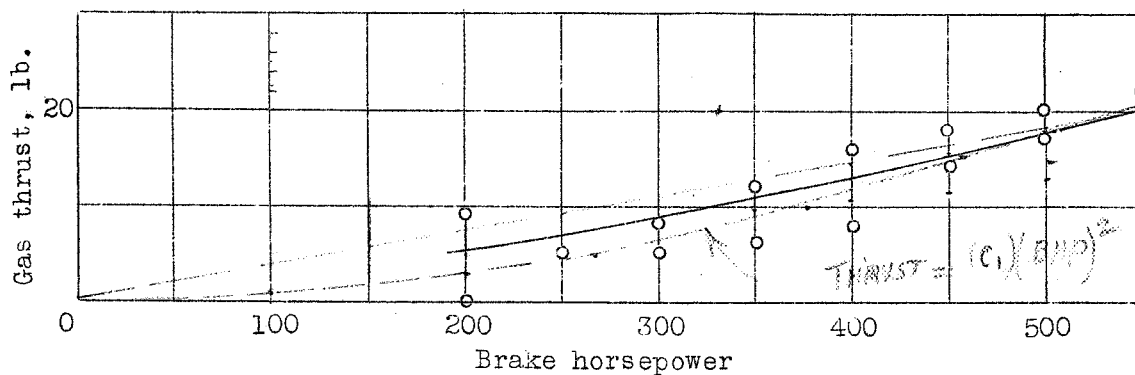


Figure 8.- Effect of engine power on exhaust gas thrust. Exhaust manifold with elbow.

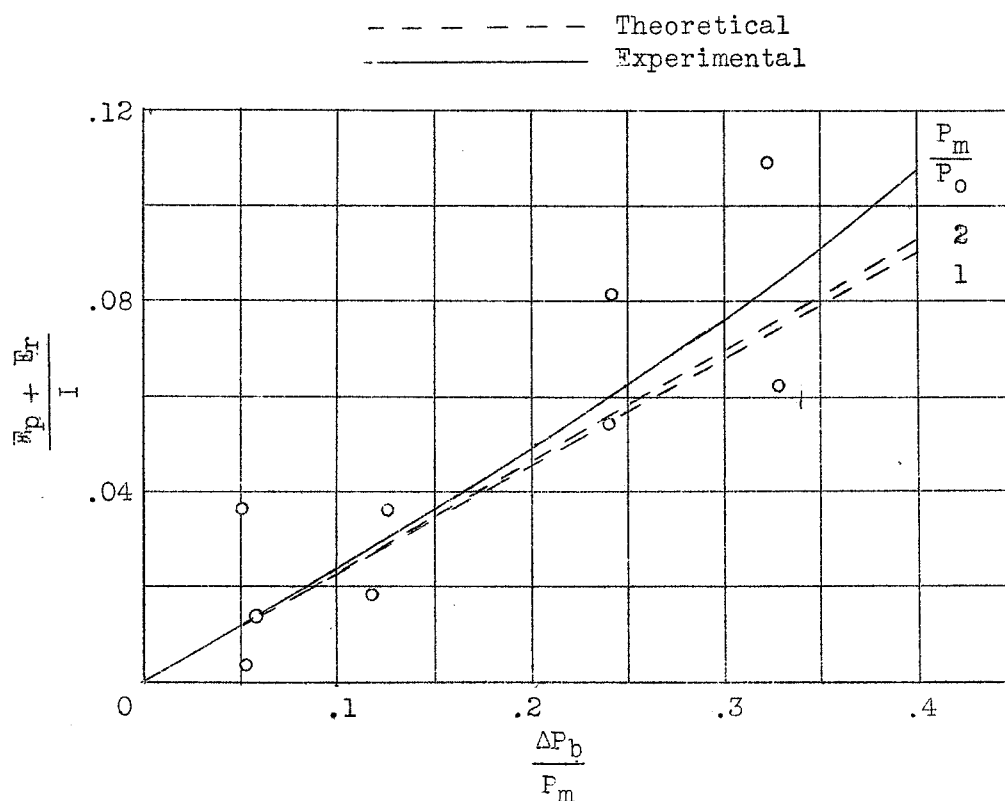


Figure 10.- Effect of ratio of increase in back pressure to manifold pressure on engine power loss per indicated horsepower.

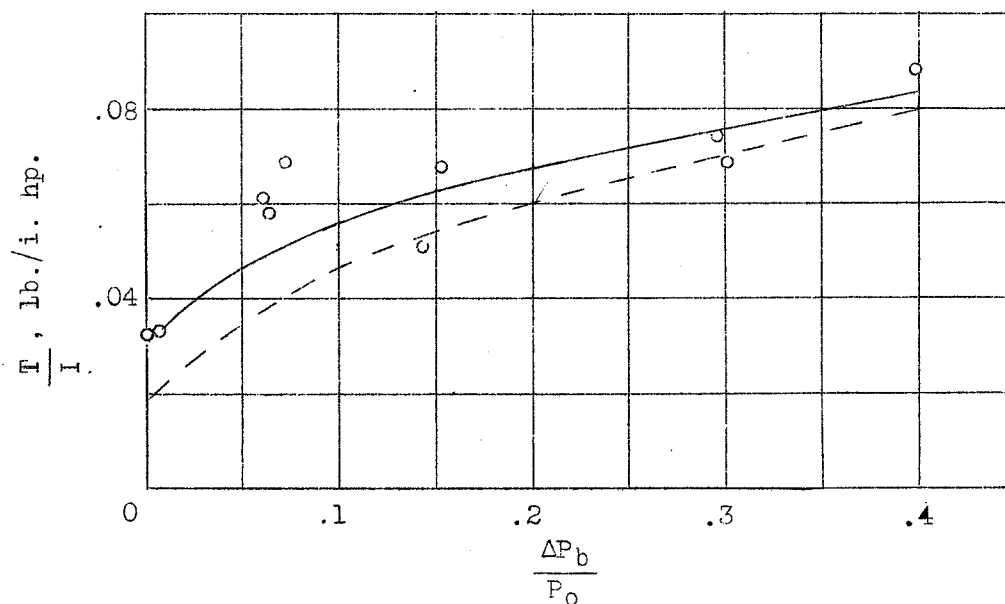


Figure 11.- Effect of ratio of increase in back pressure to atmospheric pressure on exhaust gas thrust per indicated horsepower.

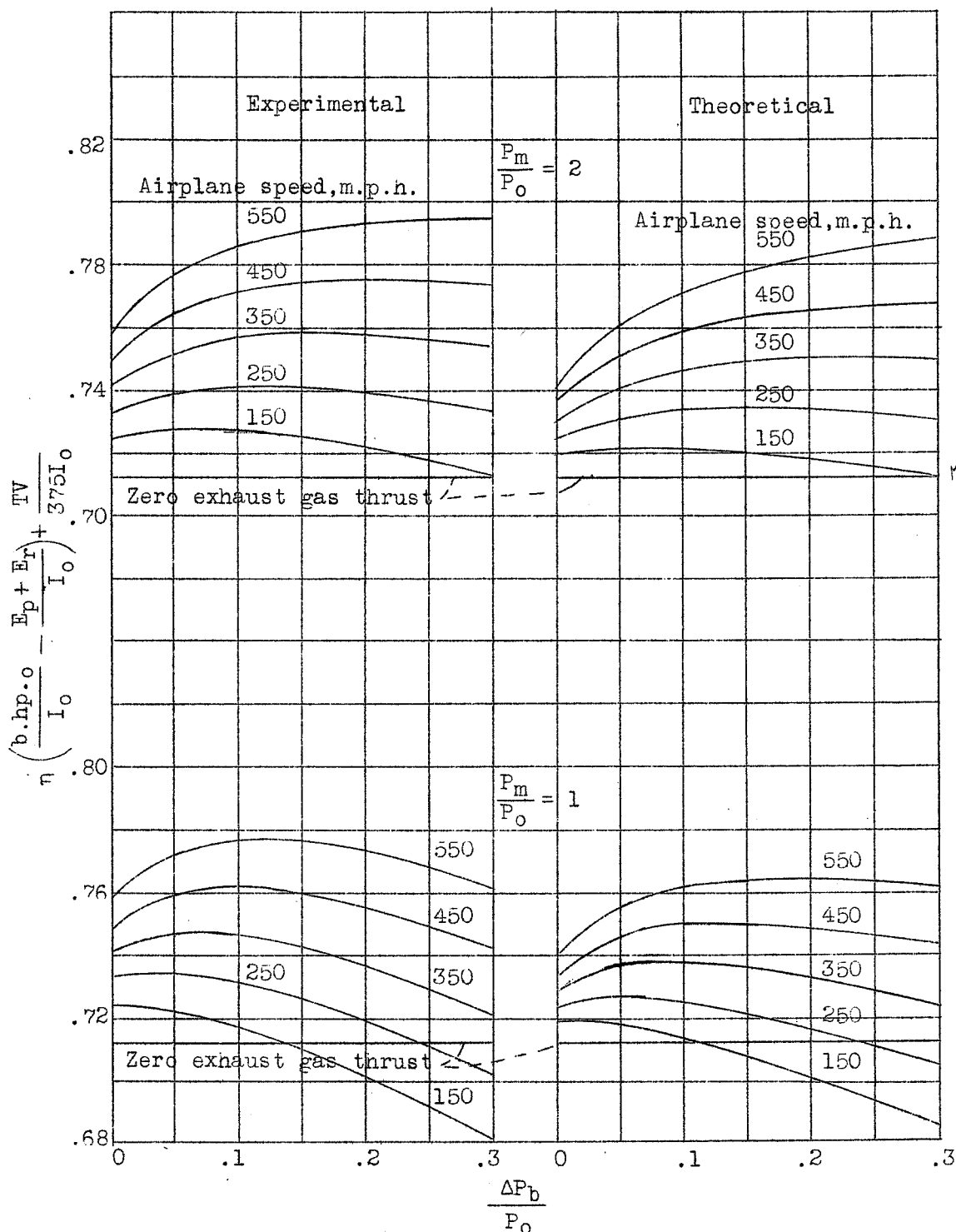


Figure 12.- Effect of ratio of increase in back pressure to atmospheric pressure on net thrust horsepower per indicated horsepower. η , propeller efficiency=80 percent.

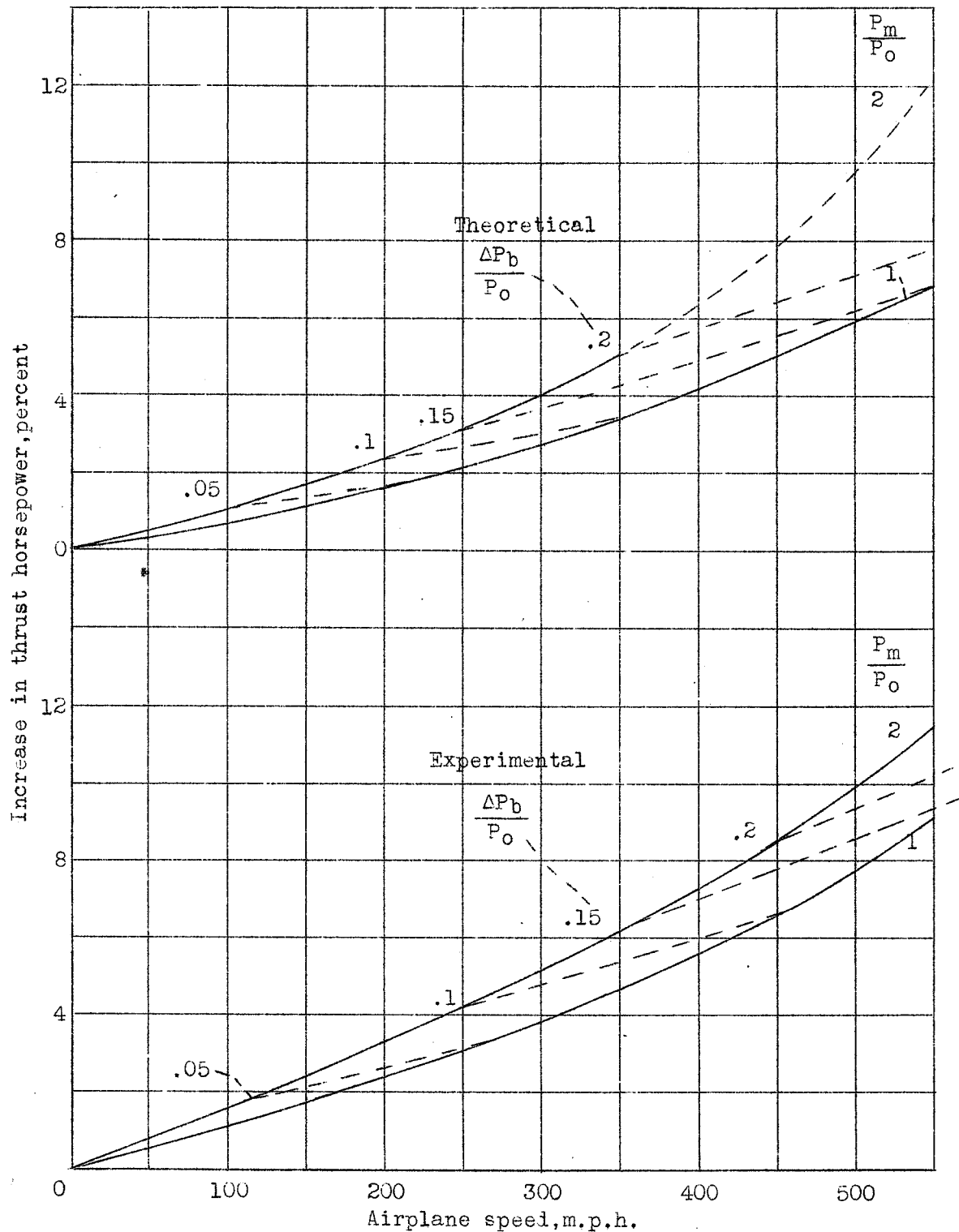


Figure 13.- Variation of percentage increase in maximum net thrust horsepower with airplane velocity for collector ring equipped with nozzle.

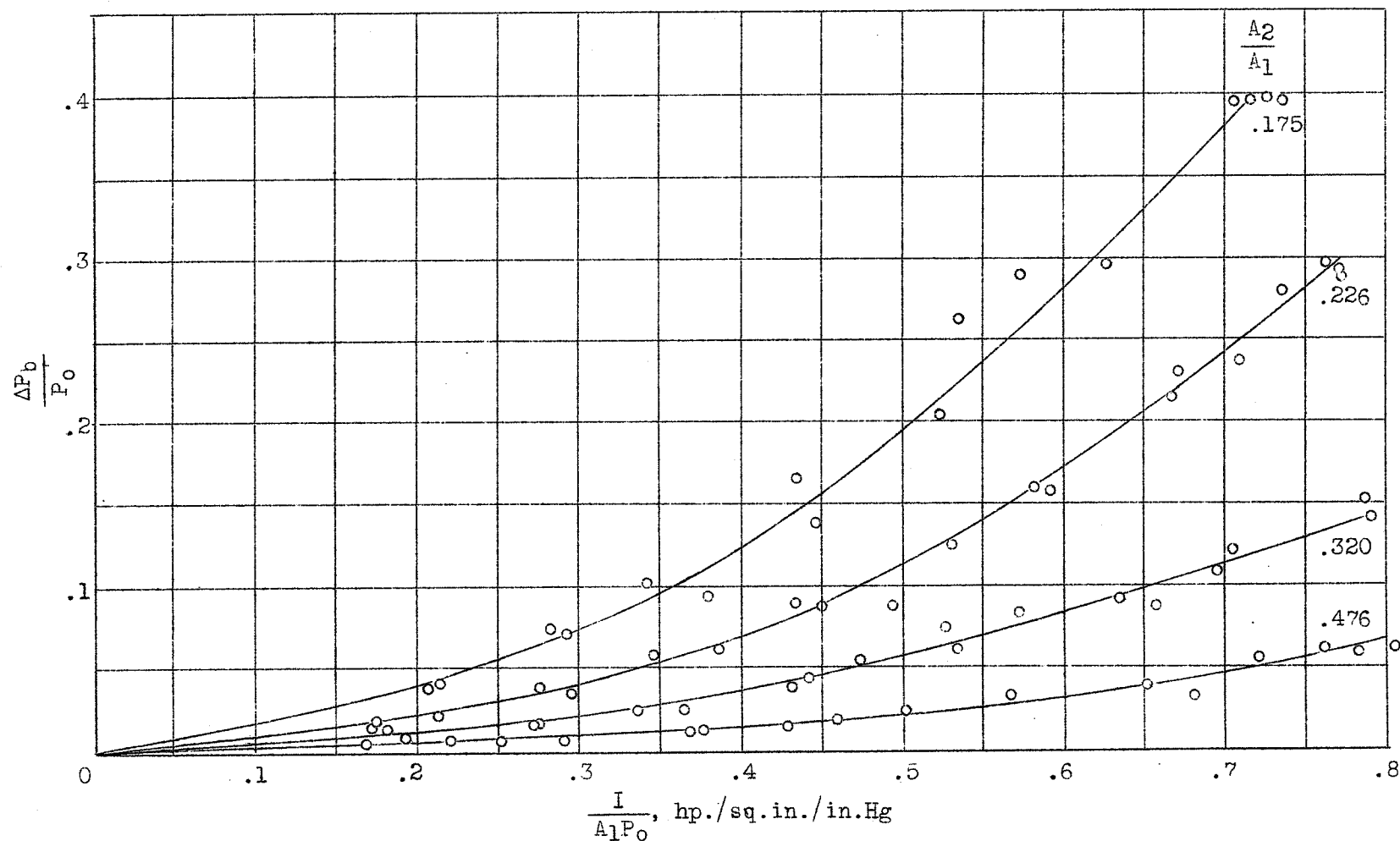


Figure 14.- Variation of the ratio of increase of back pressure to atmospheric pressure with the indicated horsepower per square inch of manifold outlet area per inch Hg atmospheric pressure and with the ratio of the nozzle area to the manifold outlet area.